

Performance Assessment of the Exploration Water Recovery System

D. Layne Carter, David Tabb, and Jay Perry

National Aeronautics and Space Administration

ABSTRACT

A new water recovery system architecture designed to fulfill the National Aeronautics and Space Administration's (NASA) Space Exploration Policy has been tested at the Marshall Space Flight Center (MSFC). This water recovery system architecture evolved from the current state-of-the-art system developed for the International Space Station (ISS). Through novel integration of proven technologies for air and water purification, this system promises to elevate existing system optimization.

The novel aspect of the system is twofold. First, volatile organic compounds (VOC) are removed from the cabin air via catalytic oxidation in the vapor phase, prior to their absorption into the aqueous phase. Second, vapor compression distillation (VCD) technology processes the condensate and hygiene waste streams in addition to the urine waste stream. Oxidation kinetics dictate that removing VOCs from the vapor phase is more efficient. Treating the various waste streams by VCD reduces the load on the expendable ion exchange and adsorption media which follows, as well as the aqueous-phase catalytic oxidation process further downstream. This paper documents the results of testing this new architecture.

INTRODUCTION

The International Space Station (ISS) Water Recovery System (WRS) is the state-of-the-art for space-based water recycling, using vacuum distillation, filtration, adsorption, ion exchange, and liquid phase catalytic oxidation to process urine and humidity condensate to potable water specifications. The ISS Trace Contaminant Control System (TCCS) is the state-of-the-art for a space-based air quality control (AQS) system. The TCCS employs vapor-phase adsorption and thermal catalytic oxidation unit operations to remove the broad spectrum of trace chemical contaminants from cabin air. To address limitations with the ISS WRS, these two systems have been functionally integrated in a proposed architecture for lunar surface exploration missions, hereafter referred to as the Exploration Water Recovery System (EWRS). The proposed architecture uses the

ISS technologies in a unique integration of unit operations to optimize treatment of the various waste water streams to improve the overall WRS robustness while reducing the logistics resupply mass requirements. The performance improvement made by changing the integration of these ISS-based technologies is anticipated to achieve a more attractive water recovery system for use in long term space exploration vehicles.

The novel aspect of the proposed approach is twofold. First, volatile organic contaminants in the cabin air are removed via catalytic oxidation before their absorption into humidity condensate in the Temperature and Humidity Control (THC) system Condensing Heat Exchanger (CHX). Vapor-phase catalytic oxidation is inherently more efficient due to the reaction kinetics because the aqueous phase mass transfer rates do not apply to the organic contaminant or oxygen in the vapor phase. This improvement thereby reduces the water recovery system complexity and logistics resupply mass requirements. Second, the VCD technology processes the urine, hygiene wastes, and condensate from the THC CHX, reducing reliance on ion exchange and adsorption media as currently done in the ISS WRS. This modification will also improve the robustness of the WRS while significantly reducing logistics resupply requirements. This concept also allows for further reduction of resupply requirements with the development of a brine processor, an option not available with the existing multifiltration technology.

TEST DESCRIPTION

A simplified schematic of the EWRS is provided by Figure 1. This new configuration was designed to utilize a high throughput catalytic reactor for the removal of volatile organic compound (VOC) species in the cabin air. By this process, the VOC load in the condensate is significantly reduced thus reducing reliance on the aqueous phase catalytic reactor currently employed in the ISS WRS. In addition, the humidity condensate is combined with pre-treated urine for processing by the VCD technology. This modification reduces the WRS logistics resupply penalty by concentrating contaminants in the VCD brine, which is more efficient than contaminant loading on adsorbent and ion exchange media.

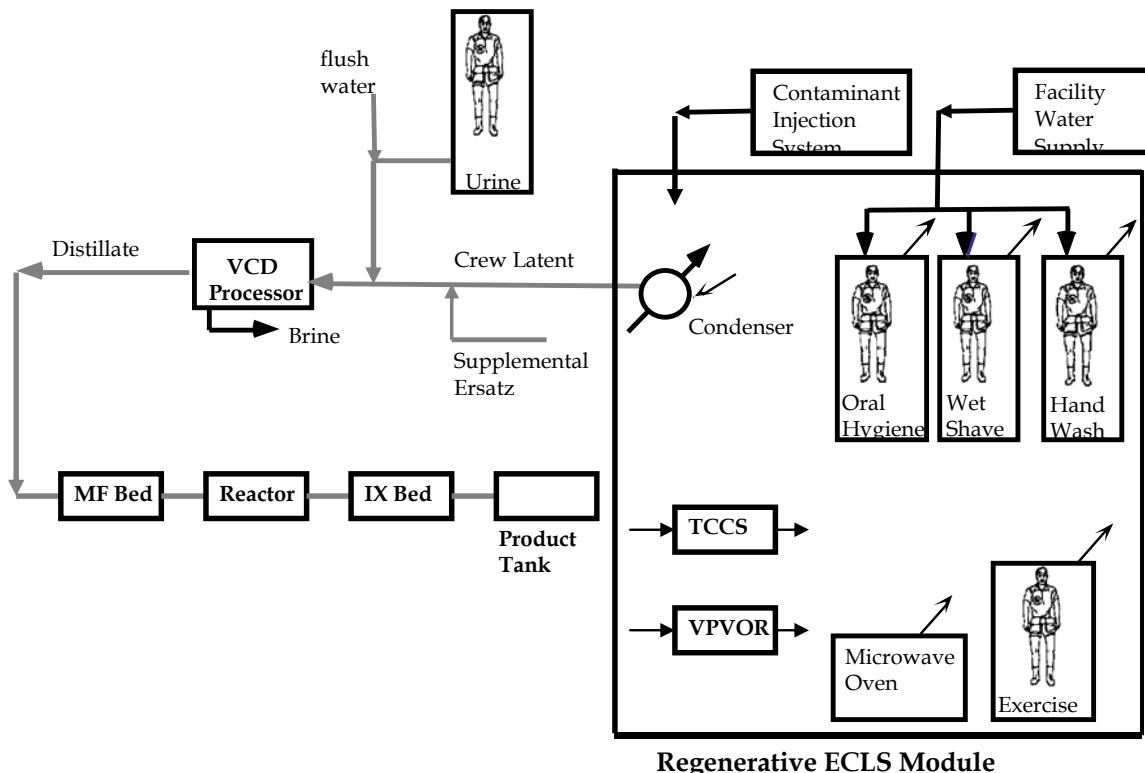


Figure 1. Simplified Schematic of the Exploration Water Recovery System

TESTING OVERVIEW

The Regenerative Environmental Control and Life Support System (ECLSS) Module Simulator (REMS) served as the backbone for testing operations. Humidity condensate was generated in the REMS from multiple sources including human perspiration and respiration. Test participants exercised to generate the humidity load and used facility water to perform three different hygiene activities—tooth brushing, wet shaving, and hand washing. Hygiene water was captured in a hand towel and allowed to dry inside the REMS. Finally, frozen dinners were heated in a microwave oven. The VOC concentrations were measured in near real-time and targeted VOCs of interest, listed by Table 1, were injected to bring the contaminant load up to levels similar to the ISS.

COMPOUNDS SELECTED FOR INJECTION - Assessing spacecraft cabin air quality and water processing equipment challenges identified 21 chemical contaminants of interest. Of these, 16 candidates for injection were selected. These compounds are typically produced by material and equipment offgassing. Table 1 summarizes the target concentration and injection rate for each compound. Another 5 compounds – urea, ammonia, methane, carbon monoxide, and hydrogen – were not injected because they are produced primarily by human metabolism. All 21 compounds were targeted for monitoring throughout the test operations.

The REMS cabin air passed through a photocatalytic-oxidation-based Vapor-Phase Volatile Organic Reactor (VPVOR) to remove VOCs in the vapor phase. Simu-

lated TCCS and removal equipment were provided. The CO₂ levels were maintained below 1.2%.

TRACE CHEMICAL CONTAMINANT CONTROL - The AQS system processes employed during the test included removing trace VOC and CO₂ removal. Traditional activated carbon adsorption and ambient temperature carbon monoxide oxidation process equipment provided basic trace chemical contamination control. Phosphoric acid-treated activated carbon manufactured by Barnebey-Sutcliffe Corp. and an ambient temperature carbon monoxide catalyst (LT CAT)

Contaminant	Minimum Rate (mg/hr)	Maximum Rate (mg/hr)	Concentration (mg/m ³)
Methanol	6.65	6.65	0.3
Ethanol	134.76	134.77	7.6
2-propanol	5.12	5.12	0.3
Benzyl alcohol	5.06	5.23	0.03
1,2-propanediol	38.18	38.24	1.3
Methanal	2.90	3.18	0.05
Ethanal	3.18	3.18	0.2
Dimethylbenzene	2.03	2.03	0.14
2-butoxyethoxyethanol	0.95	1.08	0.002
Dichloromethane	1.19	1.19	0.08
2-propanone	3.47	3.47	0.52
Diacetone	0.09	0.09	0.00033
Formic acid	5.97	6.00	0.14
Acetic acid	11.95	11.97	0.37
Benzoic acid	0.67	0.69	0.0045
Caprolactam	3.49	3.67	0.015
Urea	0	0	0.0024
Ammonia	0	0	0.049
Methane	0	0	9.1
Carbon monoxide	0	0	0.22

Hydrogen	0	0	1
----------	---	---	---

Table 1. Trace Contaminant Target Concentrations and Injection Rates

manufactured by Modern Safety Techniques (MST) were placed into a single fixed bed configuration. The test chamber air flowed through the activated carbon before contacting the carbon monoxide oxidation catalyst. Total flow through the contamination control unit was $15 \text{ m}^3/\text{hr}$ ($9 \text{ ft}^3/\text{minute}$) to yield a carbon monoxide catalyst contact time of ~ 0.5 seconds.

Carbon dioxide removal equipment employed Sodasorb (W.R. Grace, Cambridge, MA USA). Sodasorb is a soda lime product available in pellet form. Soda lime is a mixture of calcium oxide with sodium or potassium hydroxide. The Sodasorb media is treated with an indicator that changes color as the material reacts with carbon dioxide.

PRETREATMENT OF VENTILATION AIR STREAM - A primary area for investigation was the attempt to treat 100% of the ventilation air stream before it entered the condensing heat exchanger assembly. The objective was to evaluate the efficacy of a commercial photocatalytic air cleaner unit designed for use in ventilation ducts. The unit selected, the Genesis Air (Lubbock, Texas USA) Model 2002LB in-line unit, is rated for $\sim 57 \text{ m}^3/\text{minute}$ ($\sim 2,000 \text{ ft}^3/\text{minute}$) flow and employs titania (TiO_2) coated pleated fiberglass mesh elements. Banks of ultraviolet lights illuminate the TiO_2 coated elements. Figure 2 shows the 2 Model 2002LB units without the TiO_2 elements installed.



Figure 2. Commercial Photocatalytic Oxidation-based VPVOR Unit

Two photocatalytic air cleaner units were mounted in series upstream of a flight-like ISS CHX assembly. The cabin air flowed through both units at $\sim 11 \text{ m}^3/\text{minute}$ before entering the CHX. While no attempt was made to physically optimize the photocatalytic air cleaner units for the specific application, using 2 units mounted in series and operating at $\sim 20\%$ of the units' rated flow capacity was deemed a reasonable operational approach that served to increase the contact time with the TiO_2 catalyst elements.

To ensure photocatalytic activity, the relative humidity must be maintained between 30% and 60% to produce a sufficient hydroxyl radical concentration within the photocatalytic units. Cabin relative humidity conditions to ensure photocatalytic activity, the relative humidity must be maintained between 30% and 60% to produce a sufficient hydroxyl radical concentration within the photocatalytic units. Cabin relative humidity conditions were maintained at all times within this range. During quiescent periods, water was injected into the chamber to maintain the humidity level while test volunteers provided sufficient moisture introduction into the chamber while exercising.

Urine was collected in the men's restroom facility at the ECLS Test Facility. Flush water and pretreatment chemicals (chromium trioxide and sulfuric acid) were added to the urine in proportion to that employed on ISS. The pretreated urine and humidity condensate were combined as the feed to the EWRS. In batch mode, the combined waste water was passed through the Vapor Compression Distillation (VCD) processor, and then through the multifiltration beds, the catalytic reactor, and the ion exchange bed before delivery to the product tank. The waste materials removed by the VCD were stored in a brine tank.

One of the objectives of the test was to verify the VCD could achieve 94.5% recovery of the feed water before solids precipitation in the brine loop occurred. The Multi-filtration Bed protected the catalytic reactor from inorganics and aromatic hydrocarbons in the VCD distillate. This bed contained 246 cm^3 (15 inch 3) of 580-26 (manufactured by Barnebey-Cheney) and 2769 cm^3 (169 inch 3) of MB-150 (manufactured by Rohm & Haas). The Catalytic Reactor contained approximately 1081 cm^3 (66 inch 3) of Hamilton Sundstrand catalyst, equivalent to the catalyst used in the ISS Water Processor Assembly. The reactor operated at 93°C (200 °F), and at the flow rate of the distillate as delivered by the VCD, typically 1.1 to 1.8 kg/hr (2.5 to 4 lb/hr). The Ion Exchange Bed downstream of the reactor removed residual by-products of the oxidation reaction, and contained 4818 cm^3 (294 inch 3) of IRN-78, 508 cm^3 (31 inch 3) of IRN-150, and 328 cm^3 (20 inch 3) of MCV resin.

The goal of the processor is to produce water that meets the quality specifications listed in Table 2.

TEST OPERATIONS

Parameters	Specifications(a)
Physical	
Total Solids	100 mg/l
Color True	for reference only
Taste	for reference only
Odor	for reference only
Particulates	40 microns (max size)
PH	4.5 - 8.5
Turbidity	1 NTU
Dissolved Gas (1)	(free at 37°C)
Free Gas (1)	(S.T.P.)
Inorganics Constituents	
Ammonia	0.5 mg/l
Arsenic	0.01 mg/l
Barium	1.0 mg/l
Cadmium	0.005 mg/l
Calcium	30 mg/l
Chlorine (total-includes chloride)	200 mg/l
Chromium	0.05 mg/l
Copper	1.0 mg/l
Iodine (total-includes organic iodine)	15 mg/l
Iron	0.3 mg/l
Lead	0.05 mg/l
Magnesium	50 mg/l
Manganese	0.05 mg/l
Mercury	0.002 mg/l
Nickel	0.05 mg/l
Nitrate (NO ₃)	10 mg/l
Potassium	340 mg/l
Selenium	0.01 mg/l
Silver	0.05 mg/l
Sulfate	250 mg/l
Sulfide	0.05 mg/l
Zinc	5 mg/l
Bactericide	
Residual Iodine (minimum)	1 mg/l
Residual Iodine (maximum)	4 mg/l
Aesthetics	
CO ₂	15 mg/l
Microbial	
Total count: Bacteria /Fungi	100 CFU/100 ml
Total Coliform	Nondetectable
Virus	Nondetectable
Organic Parameters (2)	
Total acids	500 micro gm/l
Cyanide	200 micro gm/l
Volatile organics	< EPA MCL per EPA method 524.2, rev. 4
Semi-volatile organics	< EPA MCL per EPA method 625
Total Alcohols	500 micro gm/l
Total Organic Carbon (TOC)	500 micro gm/l
Uncharacterized TOC (UTOC) (3)	for reference only
Notes:	
(a) Maximum Contamination Level.	
(1) No detectable gas using a volumetric gas vs. fluid measurement system - excludes CO ₂ used for aesthetic purposes.	
(2) Each parameter/constituent maximum contamination level must be considered individually and independently of others.	
(3) UTOC equals TOC minus the sum of analyzed organic constituents expressed in equivalent TOC.	

Table 2. Facility and Reclaimed Potable Water Quality Specification

The test ran in batch mode in a 24-hour cycle, processing an entire day's worth of collected waste water at one time, rather than processing it as it was generated. The expected test duration was 30 days, which was the length of time required to achieve 94.5% recovery of the feed water given nominal daily processing rates. However, due to actual waste water generation rates, the test was completed in 22 days.

Each day began with transferring water from the humidity condensate collection tank and from whichever of the two urine storage tanks was currently in use simultaneously with the draining and discarding of the product tank from the previous day's product water. For at least the first hour of processing, water from the effluent of the Ion Exchange Bed was automatically rejected back to the inlet of the VCD. This continued until the product water's conductivity fell below 3 μ hos/cm. At that point the water was automatically delivered to the product tank. Samples were taken a minimum of one hour after delivery of water to the product tank started according to the schedule defined in Table 3.

During the day, while the processor ran, test subjects generated humidity condensate in the REMS through a variety of activities, filling the condensate tank for the following day. Meanwhile, urine collected in the men's bathroom of the test facility was mixed with 250 ml per liter of flush water and 16.7 ml per liter of stabilizer. The stabilizer was 54.5% deionized water, 36.5% sulfuric acid (H₂SO₄) and 9% chromium trioxide (CrO₃) by mass. Since CrO₃ is a toxic compound, procedures were developed to insure the pretreated urine was handled in compliance with the relevant NASA MSFC safety requirements. The pretreated urine was saturated with air at standard temperature and pressure and contained 15 mg/L Total Inorganic Carbon. In addition, 0.25% free gas as air, based on pretreated urine quantity, was added to the feed line upstream of the fluids pump to represent the expected quantity of free gas in the pretreated urine.

The daily total requirements for all water sources are listed in Table 4. The quantities represent a 6-crew load and are based on current ISS values. In those cases in which a hygiene activity could not be completed during the test day, (a full body wash, for example) an equivalent metered amount of water was placed directly onto a towel and allowed to dry inside the REMS. Additional contaminants were injected into the REMS atmosphere per Table 1 to simulate the atmospheric concentrations expected with a 6-person crew. Contaminant concentrations were monitored for safety purposes and to ensure proper levels and monitor the VPVOR's performance.

Port	Facility (38)	Pretreat Urine (19)	Humidity Condensate (24)	Combined Waste ** (1)	Urine Brine (84)	Distillate (134)	MF bed Effluent (126)	Reactor Effluent (205)	IX Bed Effluent (127)	Prod Tank* (120)	Total***
pH/Cond	1	3	3	5		3	1	3		5	
Spec Grav, Ref Ind					1						
Oxid Red. Potent'l		1									
Metals	A					2				1	
Cations	A					2				1	
Anions	A					2				1	
Total Iodine, I ₂ , I-	1									1	
TC, TIC, TOC	1	3	3	5		5	5	3			
TOC (low level)	A									5	
Alcohols			3			5		2		1	
Acids						2		2			
Sulfide						1					
Cyanide						1					
Semivolatiles						1				1	
Volatiles			3			1		2		1	
Glycols			3			2					
Nonvolatiles						1					
Aldehydes						1					
Total Bacteria	1					1	1			1	3
Archive (100 ml)			1	1		3	3			3	

A - Samples will be taken when Facility Tank is filled and sterilized

* Test Tank sample shall be pulled after processing a minimum of 75% of the waste feed

** Combined Waste sample shall be pulled after all waste water has been delivered

*** not including facility tank samples

General Notes:
 Pretreated Urine and Humidity Condensate samples will be taken on the same day
 All Humidity Condensate parameters will be sampled on the same day (and archive will be taken on one of these days)

Table 3. Sample Schedule for Water Recovery System

RESULTS

The EWRS test began on 28 August 2007 and was completed on 28 September after 22 days of operation. During the test, 531 kg (1171 lb) of waste water comprised of pretreated urine and condensate was processed to 94.5% recovery by the VCD in 443 hours of process mode. No precipitation in the primary processor was observed, indicating this recovery rate is viable for this waste water composition. The solids concentration in the brine at the completion of the test was measured at 19.8%. The following data summarizes the throughput through the remainder of the EWRS and takes into account water removed for samples:

- Multifiltration Bed – 518 kg (1142 lb)
- Catalytic Reactor – 512 kg (1129 lb)
- Ion Exchange Bed – 508 kg (1121 lb)

AIRBORNE CONTAMINANTS - Total concentration of airborne non-methane VOCs in the REMS atmosphere was monitored by gas chromatography (GC) and Fourier transform infrared (FTIR) spectrometry and averaged approximately 11 mg/m³ for the test duration. Ethanol accounted for between ~86% and ~96% of the total VOC concentration for the compounds monitored.

VPVOR Unit Performance - Figure 3 shows the approximate trends from GC analyses of samples collected at the VPVOR unit inlet (Port 5) and outlet (Port 6). Conversion efficiency of ethanol, based on the observed concentration trends, ranged from 44% to 23%. Similar trends were observed for most other compounds with non-methane volatile organic compound removal efficiency by the VPVOR unit tending to decrease as the

Wastewater Type	Water Quantity	Cleansing Agent
Humidity Condensate	9.6 kg/day	None
Handwash	12/day, 55 ml/activity	Water
Full Body Wash	6/day, 55 ml/activity	Water
Wet Shave	6/day, 55 ml/activity	Edge Gel
Oral Hygiene	12/day, 28 ml/activity	Crest Mint Crest Colgate
Pretreated Urine + Flush Water	8.98 kg/day	N/A

Table 4. CWP Wastewater Definition

test progressed. Table 5 summarizes the VPVOR unit's efficiency at the beginning and end of the test. These observations indicate that the photocatalytic activity is easily susceptible to performance decay. Investigating the mechanism of the performance loss and its potential reversibility was beyond the scope of the testing effort. However it is likely that any process employing photocatalytic oxidation as a process technology will have to address long-term performance reliability issues.

Compound	Efficiency (%)	
	Early Test	Late Test
Methanol	67	40
Ethanol	44	23
2-propanol	27	13
1,2-propanediol	61	38
Ethanal	50	17
Dimethylbenzene	33	23
2-butoxyethanol	44	0
AVERAGE	46	22

Table 5. VPVOR Efficiency During Testing Operations

The VPVOR unit exhibited no removal activity for some compounds such as acetone, methane, and dichloromethane. Figures 4 and 5 illustrate the observed trends for these compounds. While dichloromethane and methane are not of concern as contaminants in humidity condensate, they do drive the design of active contamination control equipment. Their not being removed by the photocatalytic oxidation-based process was not surprising given their difficulty for removal using thermal catalytic oxidation. Acetone is a concern as a humidity condensate contaminant and its lack of removal by the VPVOR unit was a disappointing result.

A further observation was the routinely higher phenol concentration exiting the VPVOR unit relative its concentration at the entrance. A plausible hypothesis for this observation is the conversion of dimethylbenzene (xylene) to phenol by the VPVOR unit. Further evaluation is necessary to confirm this hypothesis. This result emphasizes the complex nature of photocatalytic oxidation-based processes and the detailed performance characterization necessary to ensure their safe application to spacecraft ECLS systems.

Mass Transfer between Bulk Gas and Liquid Phases - A calculation technique based on Henry's Law that was developed to predict humidity condensate volatile organic loading was used to check the correlation between the bulk atmospheric concentration and the observed loading in humidity condensate collected during the testing.[1, 2, 3] The atmospheric concentration expected to produce the observed humidity condensate loading was calculated and found to be within the relative standard error for the various chemical analysis techniques employed.

The testing results further validated observations from previous ground-based testing and in-flight atmospheric and humidity condensate loading analyses where temperature adjustment and contact surface area adjustments are necessary to reach an accurately calculated atmospheric concentration when given a specific humidity condensate loading. Adjustment of the Henry's Law constant using saturation vapor pressure ratios was used.[4] This technique produced adjustment factors which agree closely with those calculated from testing documented by reference 3, which is an important result because it expands the calculation method beyond those compounds studied by past development testing. Further accounting for annular 2-phase flow development in the heat exchanger air-side channels at high air flow velocities, the calculated gas phase concentration was found to correlate most closely with the results reported by gas chromatography analyses.[5, 6] Annular 2-phase flow in a condensing heat exchanger on board the ISS was indicated by results reported by reference 2. Annular flow in the condensing heat exchanger channels appears to develop under both ground-based and in-flight conditions based on evaluation of ground-based testing and in-flight environmental sample data results.

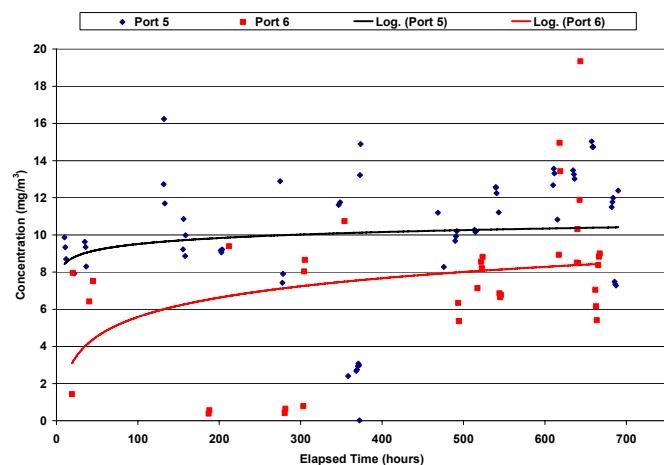


Figure 3. Ethanol Concentration Dynamics

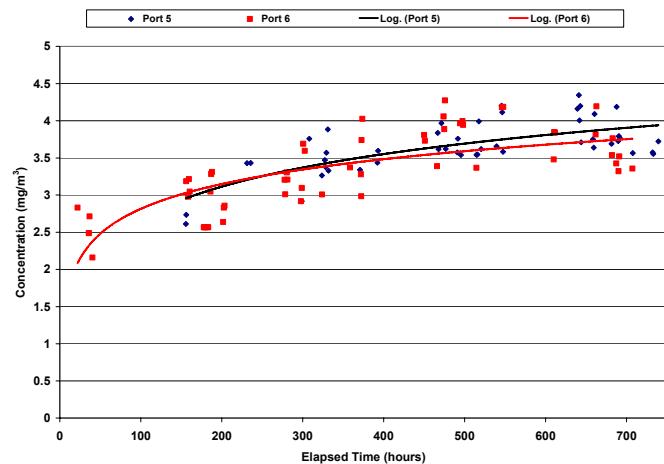


Figure 4. Methane Concentration Dynamics

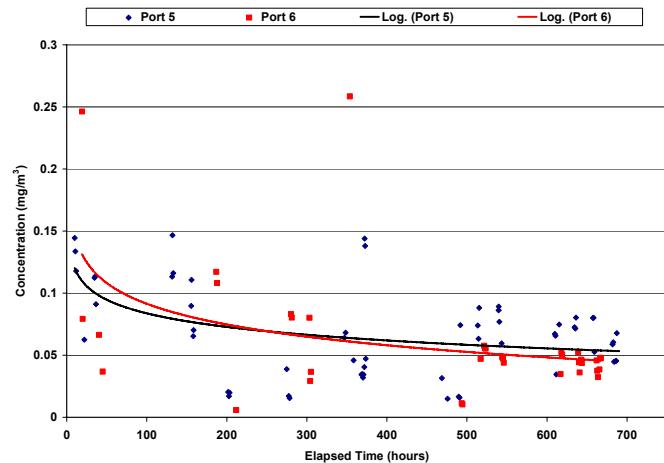


Figure 5. Dichloromethane Concentration Dynamics

EXPENDABLE RATES – After completing the test, each of the expendables was challenged with solutions to complete loading to determine their remaining capacity. The Multifiltration Bed was loaded with a solution containing 200 mg/L NaCl and 100 mg/L caprolactam, requiring 37.6 kg (83 lb) of throughput to achieve organic breakthrough and 338 for ionic breakthrough. Based on an average reduction in TOC during the test of 43 mg/L, it is estimated that the adsorbent (580-26) would provide an additional 55.8 kg (123 lb) of throughput before or-

ganic breakthrough. Based on an average influent conductivity of 300 $\mu\text{mhos}/\text{cm}$, it is estimated that the ion exchange resin (MB-150) would provide an additional 204 kg (450 lb) of throughput before ionic breakthrough. Thus, the bed capacity is 721 kg (1590 lb) for ionic contaminants and 576 kg (1270 lb) for organic contaminants. Since the MF-150 comprised 90% of the bed volume, the ion exchange capacity will be used for calculating the expendable rate. The total capacity for the bed will be estimated at 703 kg (1550 lb) throughput, which assumes 65.6 cm^3 (4 inch^3) of ion exchange resin will be replaced with adsorbent to equalize the capacity for the two media. At a mass of 8.2 kg (18 lb), this results in an expendable rate of approximately 39 kg (86 lb) throughput per kilogram of expendable for the Multifiltration Bed. This is an improvement over the ISS WRS, which achieves approximately 38.6 kg (63 lb) throughput per kilogram of expendable for the Multifiltration Bed. However, during the test, it was determined that the recycle line in the VCD was leaking through a check valve into the distillate, resulting in contamination of the feed to the Multifiltration Bed with the waste water mixture (pretreated urine and condensate). The actual conductivity in the distillate cannot be accurately defined given this hardware anomaly, though the data trend indicates that the average conductivity of 300 $\mu\text{mhos}/\text{cm}$ is approximately twice as high as the nominal given the absence of leakage from the waste water. Additional testing will be required to more accurately define the expendable rate for the Multifiltration Bed in this architecture.

The Ion Exchange Bed was loaded with a 200 mg/L NaCl solution, requiring 43 kg (94 lb) of throughput (at 1.8 kg/hr) to initiate breakthrough of the ion exchange resin. By correlating the average conductivity during the test (143 $\mu\text{mhos}/\text{cm}$) to the influent conductivity of the NaCl solution (420 $\mu\text{mhos}/\text{cm}$), it is estimated that the bed would have a total throughput of 635 kg (1400 lb). At a mass of 13.2 kg (29 lb), this results in an expendable rate of approximately 22.7 kg (50 lb) throughput per kilogram of expendable for the Ion Exchange Bed. Note that the influent conductivity to the Ion Exchange Bed was abnormally high during the test due to an anomaly associated with the Catalytic Reactor. By operating at a reduced temperature, the reactor produced a higher concentration of acetate, which subsequently reduced the pH to levels as low as 3.3. Initially the hydronium and acetate accounted for more than 2/3 of the measured conductivity, when the pH was greater than 4. But as the test progressed and the pH shifted to 3.3 to 3.5, other inorganic contaminants (including nitrate and phosphate) were also detected at elevated concentrations. The source of these contaminants is currently unknown, nor their connection with the low pH. However, additional investigation and possibly testing should identify their source and also determine if they can be eliminated as a load on the Ion Exchange Bed.

PRODUCT WATER QUALITY - An initial review of the water quality data indicates that the VPVOR had only a

minor effect on the concentration of VOCs in the humidity condensate.

The VCD was effective in processing the waste water to distillate. Table 6 summarizes VCD performance with regard to water quality.

The Multifiltration Bed, comprised of 246 cm^3 (15 inch^3) of 580-26 and 2769 cm^3 (169 inch^3) of MB-150, also performed to requirements. The adsorbent in the bed removed the non-volatile organic species to an effluent TOC averaging 29 mg/L during the test, while the ion exchange resin provided an effluent conductivity that was consistently $<5 \mu\text{mhos}/\text{cm}$.

The Catalytic Reactor is a critical component in the EWRS architecture, as it must operate at a reduced temperature while still completing oxidation of the various volatile organics to CO_2 (complete oxidation) or to the corresponding organic acid for subsequent removal by the Ion Exchange Bed. As noted previously, the TOC feed to the reactor averaged 29 mg/L during the test. The primary contaminant is ethanol, though methanol and acetone were also detected as well as trace concentrations of various other low molecular weight organics. These contaminants were typically removed to concentrations below their detection limit of 1 mg/L, with the lone exception being ethanol at 1.8 mg/L on Test Day 14. The TOC in the reactor effluent ranged from <0.5 to 6.7 mg/L, and was primarily comprised of acetate, an oxidation product of ethanol. No other organic acids were detected above their detection limit. Most importantly, the reactor was sufficiently effective such that processing by the Ion Exchange Bed was typically adequate to meet the product water TOC requirement. Other than Test Day 1 (TOC = 5.9 mg/L), the TOC was less than the potable requirement of 3 mg/L. These data, provided in Figure 6, provide positive support to the theory that the reactor can adequately oxidize the organic load from the VCD distillate in the EWRS architecture.

Parameter	VCD Feed (average)	VCD Distillate (average)
Total Organic Carbon	1850 mg/L	72 mg/L
Conductivity	15,250 $\mu\text{mhos}/\text{cm}$	300 $\mu\text{mhos}/\text{cm}$

Table 6. Summary of VCD Water Quality Data

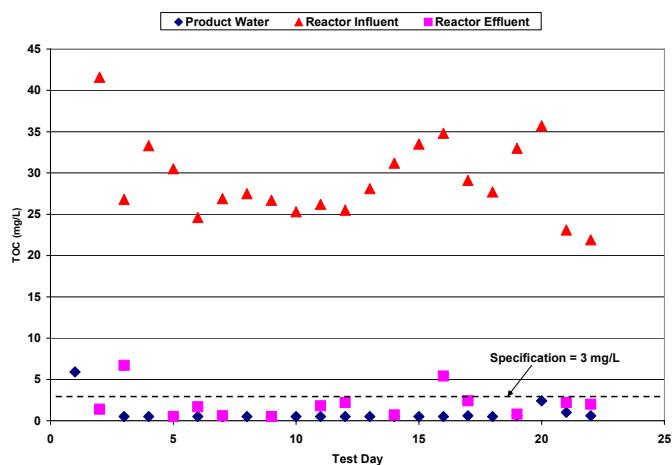


Figure 6. TOC Removal by the Catalytic Reactor

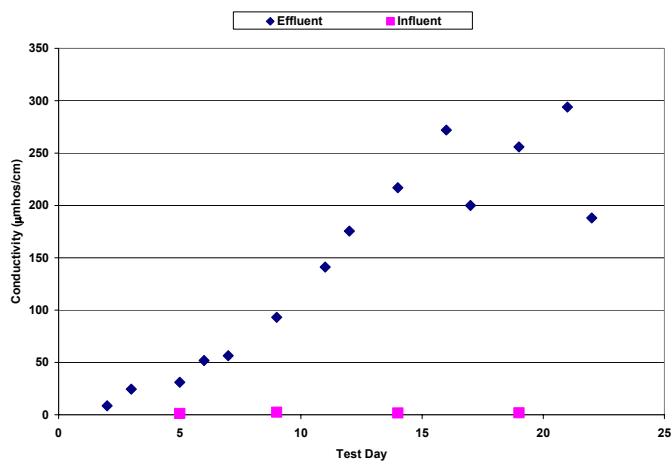


Figure 7. Reactor Influent and Effluent Conductivity

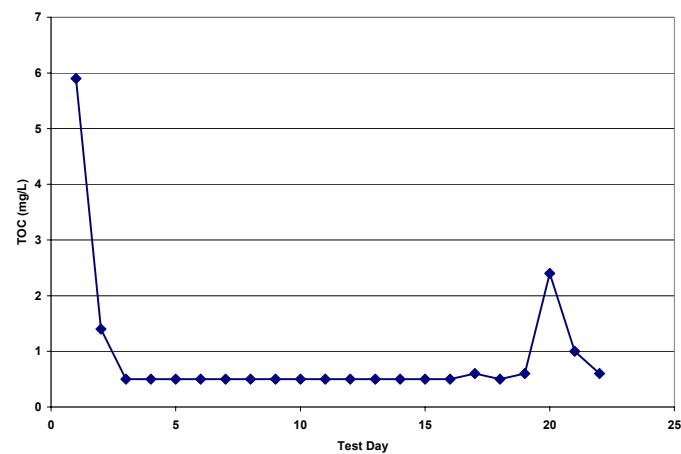


Figure 8. Product Water TOC

Though the reactor performance was positive with regard to organic removal, as mentioned previously in this report there was a surprising result with regard to the effluent conductivity. Figure 7 shows the reactor's influent and effluent conductivity. Since the influent conductivity is negligible, the effluent conductivity is obviously not due to a failure of the Multifiltration Bed. Analysis of the analytical data determined the correlation was with the effluent pH, which dropped from >5 initially to levels ranging from 3.3 to 3.5. These low pH levels resulted in high conductivity values due to the increased concentration of hydronium ions. In addition, analysis of the reactor effluent on Test Days 14 and 21 for cations, anions, and metals identified elevated levels of nitrate (61 mg/L on Day 14) and phosphate (104 mg/L on Day 21). Ammonium was detected at 3.8 and 3.0 mg/L on those test days, respectively, and no other contaminant was identified at an appreciable concentration. This data is summarized in Table 7. Due to the limited data set, a conclusive statement cannot be made regarding the source of the inorganics.

Available data indicate that the proposed EWRS architecture is capable of providing water meeting the product water requirements for the NASA's Space Exploration Policy missions. The product water conductivity ranged from 1.6 to 3.3 μ hos/cm, and pH from 5.5 to 6.8. Nickel was also detected in the product water, once at 0.13 mg/L, which exceeds the requirement of 0.050 mg/L. Nickel is present as a leachate from the stainless steel tubing, and can thus be eliminated from the product water with proper materials selection. Other than the residual iodine added to the water as a residual biocide, there were no other inorganic contaminants present in the product water. As noted previously and shown in Figure 8, the TOC requirement of 3 mg/L was violated on Test Day 1 due to the presence of ethanol (9.1 mg/L) and methanol (1.5 mg/L). After the first test day, the reactor was able to successfully oxidize the organic contaminants for subsequent removal by the Ion Exchange Bed. Also, methyl sulfone was detected at concentrations ranging from less than detection limit to 0.159

Test Day	Effluent Cond (μ hos/cm)	Acetate (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	pH	Cond from H ⁺
02	8.6	1.9			5.2	2.2
03	24.5				4.2	22.1
05	31.2	0.125			4.2	22.1
06	51.8	3.17			4	35
07	56.5				3.8	55.4
09	93.2	0.125			3.7	69.8
11	141.1	4.02			3.3	175.2
12	175.5				3.5	110.6
14	217	0.645	60.9	0.7	3.4	139.2
16	272	9.03			3.4	139.2
17	200				3.5	110.6
19	255.9	0.637			3.4	139.2
21	294	4.07	0.3	103.8	3.3	175.2
22	188	4.02			3.5	110.6

Table 7. Reactor Effluent Conductivity

mg/L. This contaminant is a residual product of the ion exchange resin.

SUMMARY

The VPVOR influent and effluent VOC data indicate that the photocatalytic oxidation-based process had a minimal impact on the VOC load entering the CHX and, therefore, loading the humidity condensate. More detailed analysis photocatalytic oxidation-based process performance is a subject for further study. In spite of this result, the data provide solid evidence that the aqueous phase catalytic reactor can be used at ambient pressure while still effectively oxidizing the organic load and removing the microbial population. However, inorganics in the VCD distillate, from leakage through the recycle line, affected the life of the Multifiltration Bed, and the low pH generated by the Catalytic Reactor also affected the life of the Ion Exchange Bed. Further testing and analysis is required to accurately define the expendable rate of these items. Most importantly, the VCD was effective in achieving 94.5% water recovery of the condensate and pretreated urine, thereby reducing a significant expendable quantity in the Multifiltration Bed.

ACKNOWLEDGMENTS

The authors would like to thank the personnel in the MSFC ECLS test facility for their exemplary effort in the completion of the test, and the Wyle Laboratory at the Johnson Space Center for their contribution in the analysis of chemistry and microbial samples from the test.

REFERENCES

1. Perry, J.L. Elements of Spacecraft Cabin Air Quality Control Design. NASA/TP-1998-207978. NASA Marshall Space Flight Center. May 1998, pp. 145-148.
2. Perry, J.L. The Interaction of Spacecraft Cabin Atmospheric Quality and Water Processing System Performance. SAE 2002-01-2300. 32nd International Conference on Environmental Systems. Toulouse, France. July 2002, p. 2.
3. Tatara, J. and Perry, J. International Space Station System-Level Trace Contaminant Injection Test. NASA/TM-1999-209010. NASA Marshall Space Flight Center. March 1999, pp. 25-26.
4. Smith, F.L. and Harvey, A.H. Avoid Common Pitfalls When Using Henry's Law. Chemical Engineering Progress. September 2007, pp. 35-36.
5. Durand, A.A.; Guerrero, C.A.A.; and Ronces, E.A.: Gravity Effects in Horizontal Condenser. Chemical Engineering. April 2002, pp. 91-94.
6. Daniels, L. Dealing with Two-Phase Flow. Chemical Engineering. June 1995, pp. 70-78.

NASA Marshall Space Flight Center
layne.carter@nasa.gov

Jay Perry
NASA Marshall Space Flight Center
jay.l.perry@nasa.gov

CONTACTS

Layne Carter